Modelling And Simulation Of The Dynamic Behaviour Of Wheel-Rail Interface

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Contents

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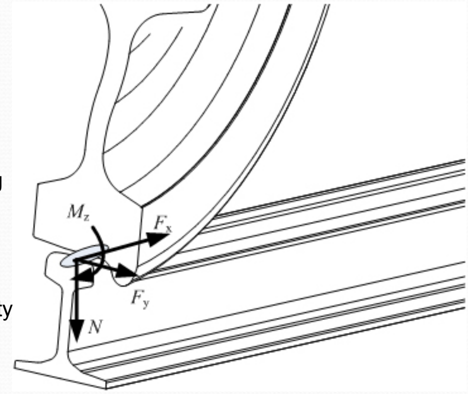
Wheel-rail contact forces

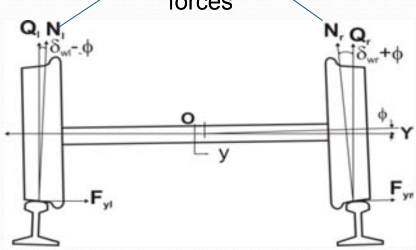
- N represents the Normal Contact Force acting directly on the rail as a result of the axle load, wheelset mass and contact angle.
- F_x represents the longitudinal creep force acting in the rolling direction of the wheel.
- F_y represents the lateral creep force acting in the lateral direction of the wheel.
- M_z represents the spin creep moment caused as a result rotation of the wheel in the vertical z direction due to wheel conicity



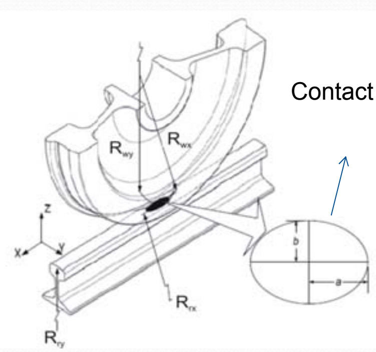
Normal Contact Problem

- Normal contact problem involves calculating the normal contact forces acting on the wheel-rail contact.
- f (contact angle, axle load of the wheelset, wheelset weight).
- The calculated normal forces are used to determine the contact patch shape, size and dimension using Hertz Contact Theory.

Normal contact forces



Contact patch



Tangential Contact Problem

- Tangential contact problem → creepages and tangential creep forces developed in the wheel-rail contact as a result of acceleration, braking or traction.
- Kalker's linear theory → lateral, longitudinal and spin creep forces (for small creepages)
- For large creepages - Heuristic non-linear model is used to limit the creep forces. Prevents excessive damage to the wheels Reduces probability of derailment
- Calculated creep forces & lateral, longitudinal and spin creep moments → determine total lateral force and spin moment force acting on the wheelset.
- The lateral and yaw behaviour of the wheelset on the track is investigated by applying Newton's 2nd law of motion.

2D WHEEL-RAIL CONTACT MODEL

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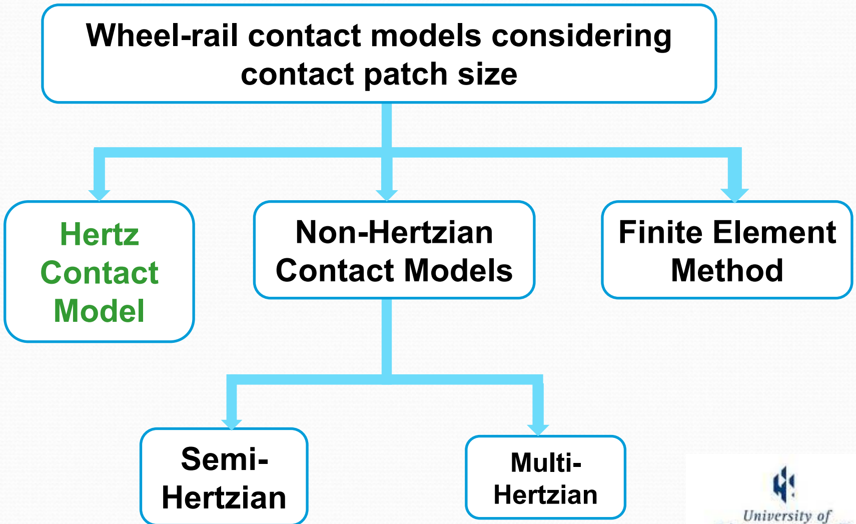
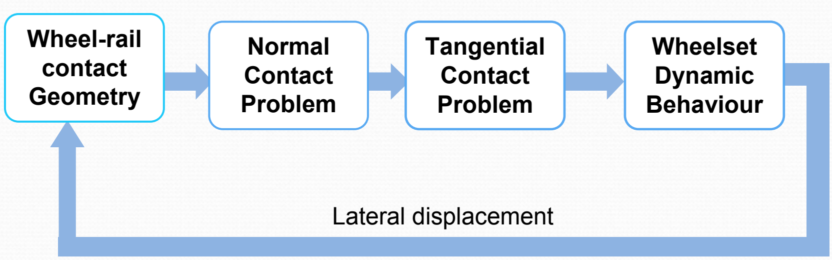
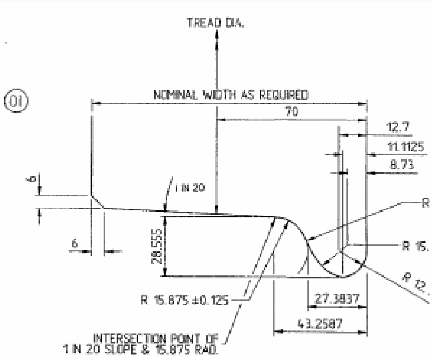
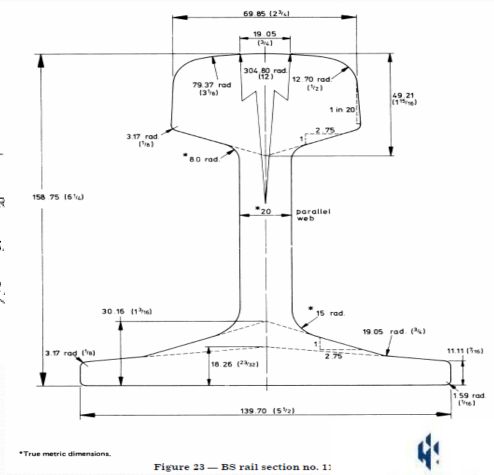


Determination of lateral displacement



Wheel-rail contact geometry





Wheel profile P1

Rail profile BS113A

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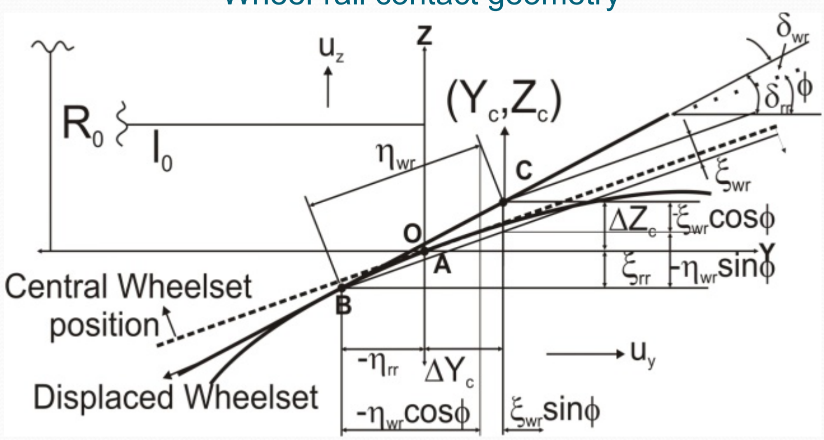
Wheel-rail contact geometry



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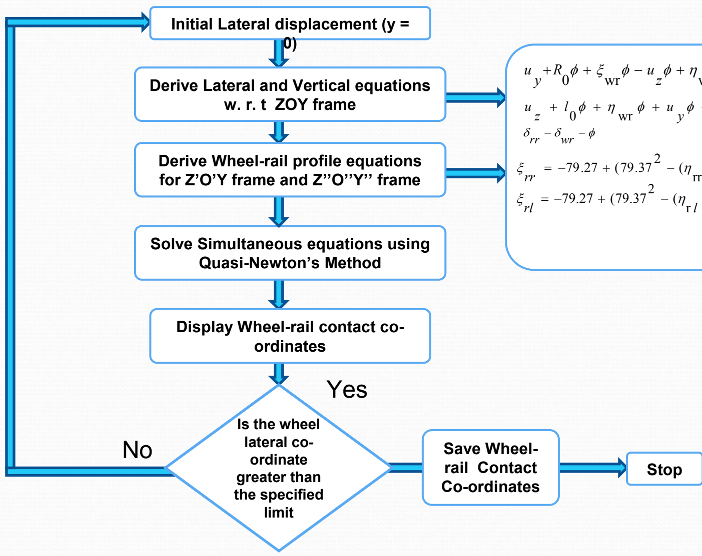
Wheel-rail contact geometry



$$u_y + R_0\phi + \xi_{wr}\phi - u_z\phi + \eta_{wr} - \eta_{rr} = 0$$

$$u_z + l_0\phi + \eta_{wr}\phi + u_y\phi + \xi_{wr} - \xi_{rr}$$

$$\delta_{rr} - \delta_{wr} - \phi$$

$$\xi_{rr} = -79.27 + (79.37^2 - (\eta_{rr} - 3.96)^2)^{1/2}$$

$$\xi_{rl} = -79.27 + (79.37^2 - (\eta_{rl} + 3.96)^2)^{1/2}$$

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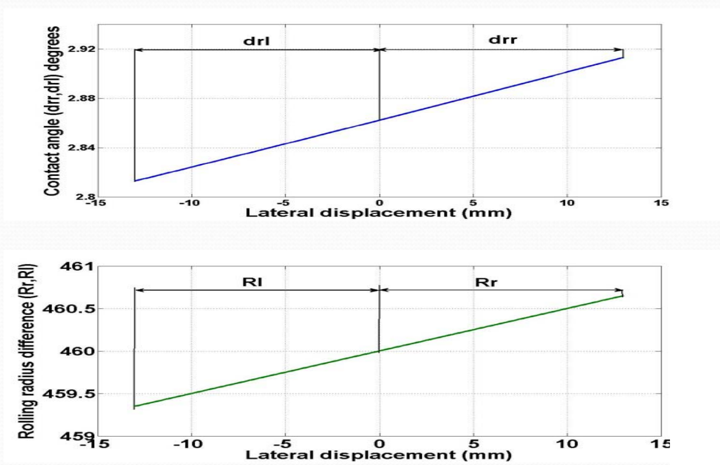
Wheel-rail contact geometry



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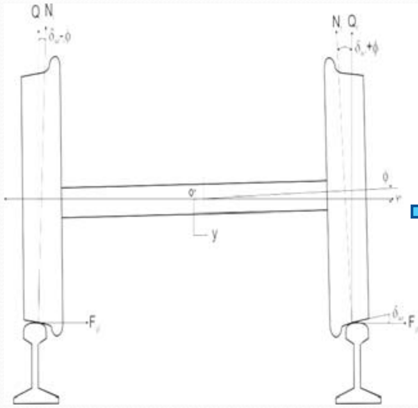
Normal Contact Problem



$$N_r \cos(\delta_{wr} + \phi) + N_l \cos(\delta_{wl} - \phi) = (W + mg)$$

$$N_r \sin(\delta_{wr} + \phi) - N_l \sin(\delta_{wl} - \phi) = -(W + mg)\phi$$

Normal Contact Problem

Relative Curvatures Coefficients

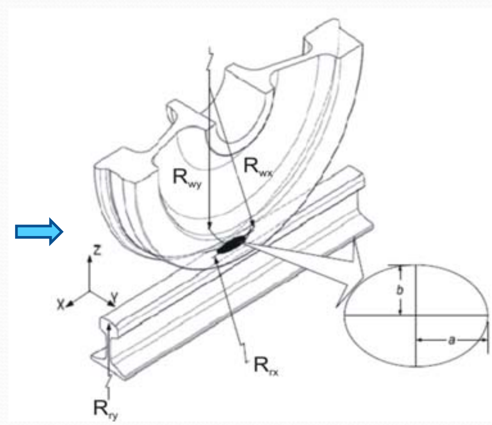
$$A = \frac{1}{2R_{wx}} + \frac{1}{2R_{wy}}$$

$$B = \frac{1}{2R_{rx}} + \frac{1}{2R_{ry}}$$

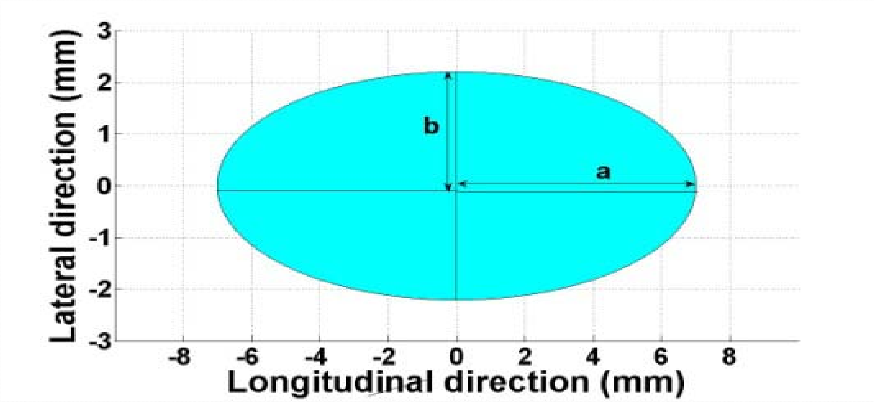
Contact patch semi-axis

$$a = m\left(\frac{3(1-v^2)}{2E(A+B)}\right)^{1/3} \times N^{1/3}$$

$$b = n\left(\frac{3(1-v^2)}{2E(A+B)}\right)^{1/3} \times N^{1/3}$$

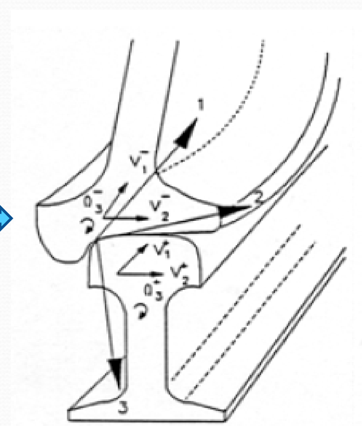


Normal Contact Problem



Tangential Contact Problem

- Longitudinal creepage $v_x = \frac{V_1^- - V_1^+}{V}$
- Lateral creepage $v_y = \frac{V_2^- - V_2^+}{V}$
- Spin creepage $v_{spin} = \frac{\Omega_3^- - \Omega_3^+}{V}$



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Tangential Contact Problem

Lateral Creepage (Left/right Wheel-rail contact)

$$v_y = \frac{dy}{dt}\left(\frac{1}{v}\right) - \psi$$

Longitudinal Creepage

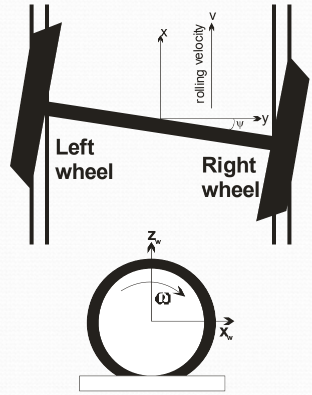
$$v_{x(left)} = \frac{l_o}{R} + \frac{\lambda y}{R_o} + \frac{l_o}{v}\left(\frac{d\psi}{dt}\right)$$

$$v_{x(left)} = -\frac{l_o}{R} - \frac{\lambda y}{R_o} - \frac{l_o}{v}\left(\frac{d\psi}{dt}\right)$$

Spin Creepage

$$\varphi_{left} = -\frac{1}{v}\frac{d\psi}{dt} + \frac{\lambda}{R_o}$$

$$\varphi_{right} = -\frac{1}{v}\frac{d\psi}{dt} - \frac{\lambda}{R_o}$$



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Tangential Contact Problem

Creepages

Kalker's Linear Theory

Calculate Creep Forces

$$F_x = -f_{11} v_x$$
$$F_y = -f_{22} v_y - f_{23} v_{spin}$$
$$M_z = -f_{23} v_y - f_{33} v_{spin}$$

Heuristic Non-Linear Model

Calculate Normalized Creep forces

$$F_x' = -aF_x$$
$$F_y' = aF_y$$
$$M_z' = aM_z$$

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Parameters for experimental test rig

I_z	Moment of inertial	1.27×10^{7}N-mm
K_{py}	Lateral spring stiffness	3.863×10^{3}N/mm
K_{px}	Longitudinal spin stiffness	850 N/mm
C_{py}	Lateral damper coefficient	8 Ns/mm
C_{px}	Longitudinal damper coefficient	100 Ns/mm
f_{11}	Longitudinal linear creep coefficient	8.06×10^{6} N
f_{22}	Lateral linear creep coefficient	8.09×10^{6} N
f_{23}	Lateral/spin linear creep coefficient	2.2×10^{7} N-mm
f_{33}	Spin linear creep coefficient	1.27×10^{7} N-mm
m	Wheelset mass	1250 kg

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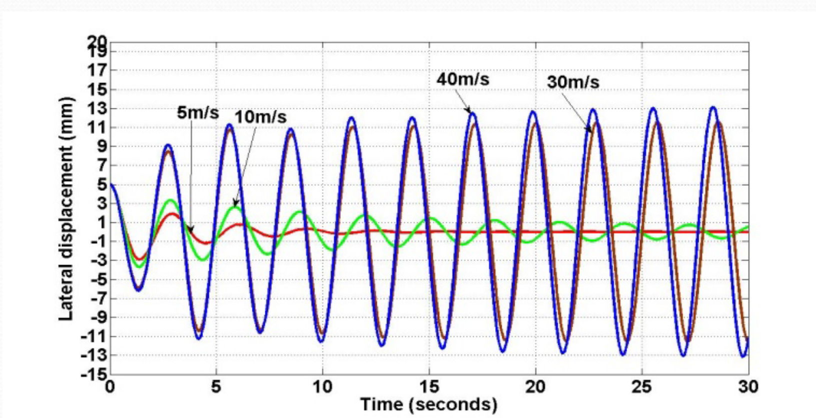
Dynamic behaviour of the Wheelset on the track using Kalker theory



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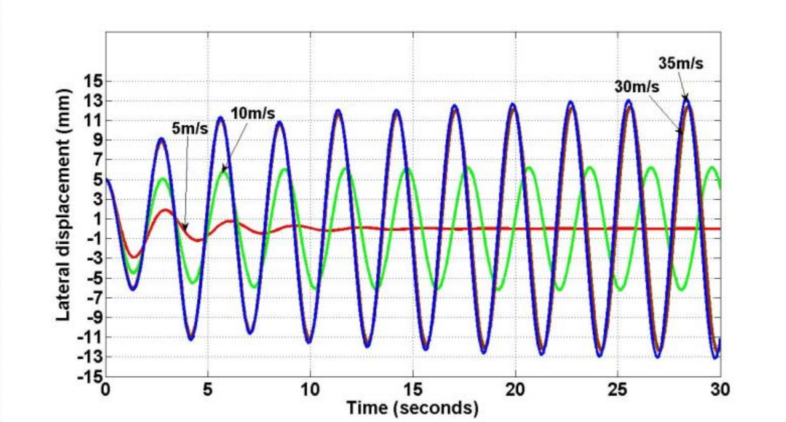
Dynamic behaviour of the Wheelset on the track using Heuristic method



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3-DIMENSIONAL WHEEL-RAIL CONTACT MODEL

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- 3D Wheel-rail contact
  - Rigid Contact Method
  - Semi-elastic methods
    - Minimum Distance method
    - Minimum Difference method

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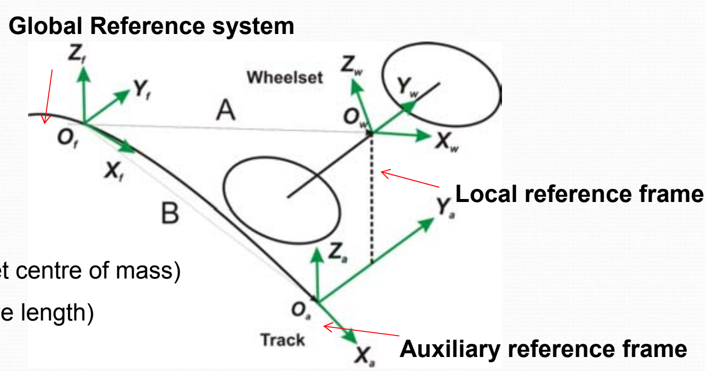
Proposed 3D Wheel-rail contact model



A = O_w^a (Wheelset centre of mass)

B = O_w^f (Rail curve length)

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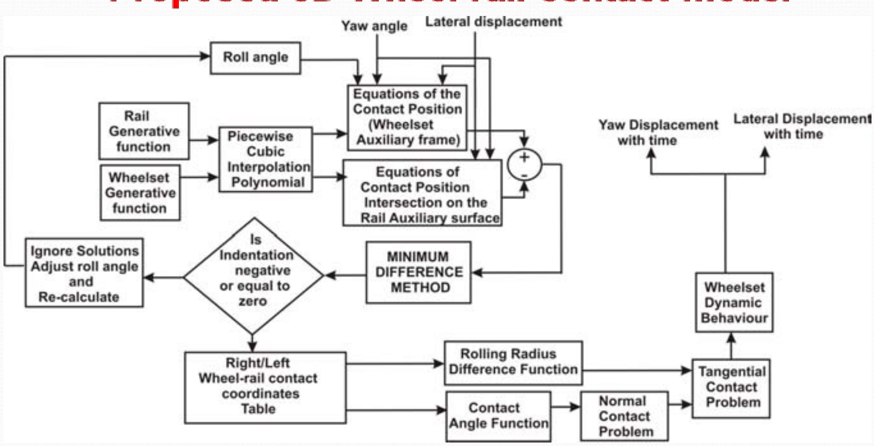
Proposed 3D Wheel-rail contact model

- Global reference system (O_f, X_f, Y_f, Z_f) defines the track as a three dimensional curve.
- The Auxiliary reference system (O_a, X_a, Y_a, Z_a) follows the wheelset during program simulation.
- The local reference system (O_w, X_w,Y_w,Z_w) is defined whereby Y_w is rigidly fixed to the wheelset axle. The origin of the wheelset O_w corresponds with the centre of gravity G of the wheelset.

Proposed 3D Wheel-rail contact model



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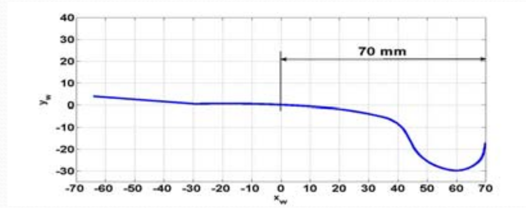
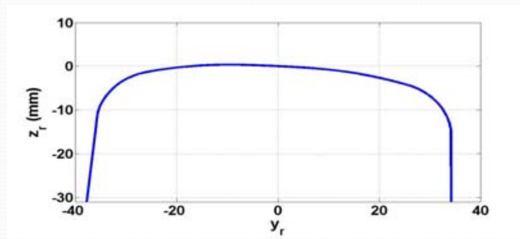
Proposed 3D Wheel-rail contact model

P8 Wheel Profile



1:20 BS113A Rail cant



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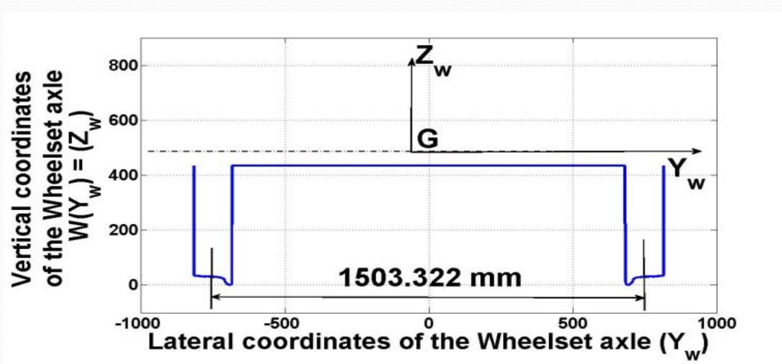
Proposed 3D Wheel-rail contact model



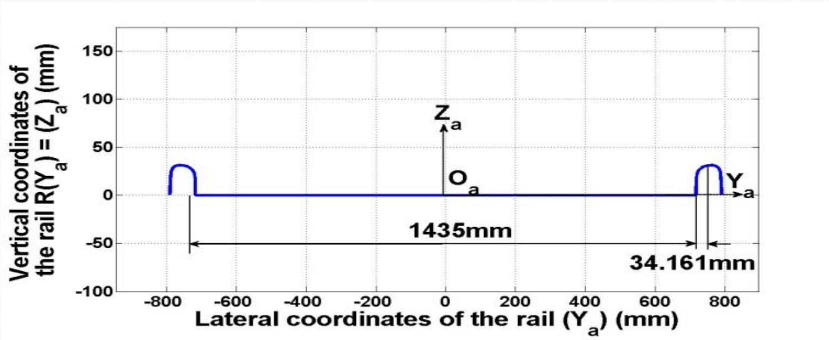
Right wheel lateral contact range

$(692 \leq Y_w \leq 815)$ mm

Left wheel lateral contact range

$(-815 \leq Y_w \leq -692)$ mm

Proposed 3D Wheel-rail contact model



Right wheel lateral contact range

$(700 \leq Y_a \leq 780)$ mm

Left wheel lateral contact range

$(-780 \leq Y_a \leq -790)$ mm

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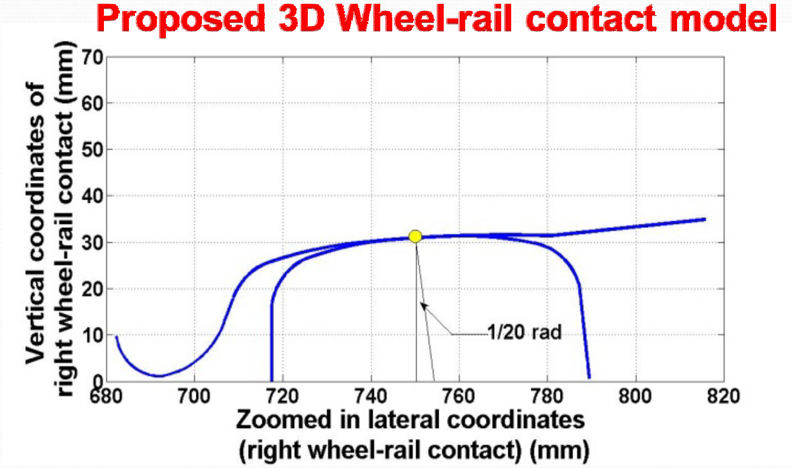
Proposed 3D Wheel-rail contact model



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Proposed 3D Wheel-rail contact model

Kinematic equation of the contact point in the Auxiliary system w.r.t the local reference frame

$$V_w^a(X_w, Y_w) = O_w^a + [A_2]V_w^w(X_w, Y_w) = \begin{bmatrix} x_w^a \\ y_w^a \\ z_w^a \end{bmatrix}$$

$$V_w^w(X_w, Y_w) = \begin{bmatrix} X_w \\ Y_w \\ -\sqrt{W(Y_w)^2 - X_w^2} \end{bmatrix} \qquad O_w^a = \begin{bmatrix} 0 \\ u_y \\ u_z \end{bmatrix} \qquad V_a^a(X_w, Y_w) = \begin{bmatrix} x_w^a \\ y_w^a \\ b(y_w^a) \end{bmatrix}$$

A_2 = Rotation Matrix (link between Local and Auxiliary Reference System)
ψ = yaw angle
ϕ = roll angle
u_y = Lateral displacement
u_z = Vertical displacement

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Proposed 3D Wheel-rail contact model

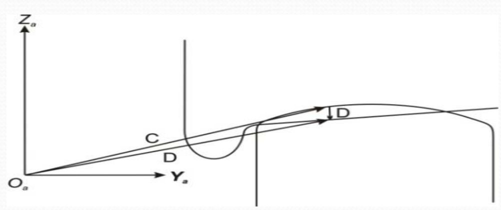
Find the local minimum between the wheel and the rail contact points

$$D(X_w, Y_w) = (V_w^a(X_w, Y_w) - V_a^a(X_w, Y_w)).C_a$$

C = $V_a^a(X_w, Y_w)$ intersection between the rail surface and line parallel to axis z_r

$$V_a^a(X_w, Y_w) = \begin{bmatrix} x_w^a \\ y_w^a \\ b(y_w^a) \end{bmatrix}$$

D = $V_w^a(X_w, Y_w)$



Take partial derivative of D and reduce to one Dimensional form

$$E_{1,2}(Y_w) = \frac{\partial D(X_w 1,2)}{\partial Y_w} = 0$$

Check for Indentation

$$I_i = D_i^a . n_a^a(V_{ai}^a) \leq 0$$

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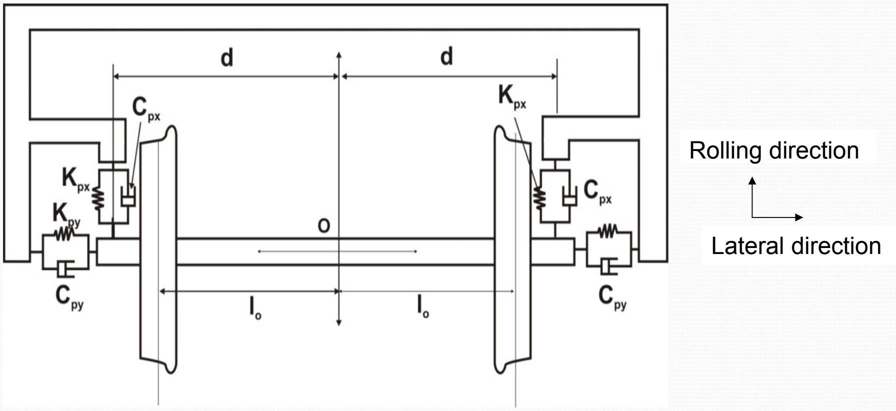
Simulated Results

Suspended Wheelset



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Simulated Results

Input Parameters	Range	Step
roll angle ϕ (rad)	0– 0.01	0.0005
Yaw angle ψ (rad)	0 – 0.01	0.0005
Lateral displacement$_y$ (mm)	0 – 10mm	0.5

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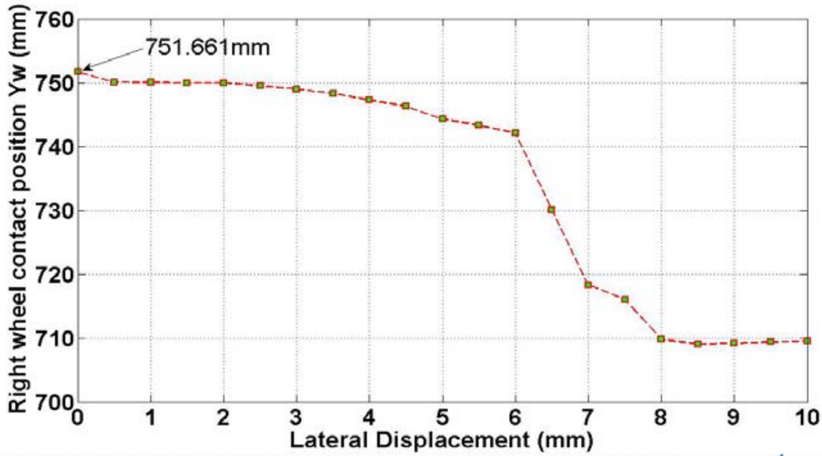

Lateral contact positions on the right wheel

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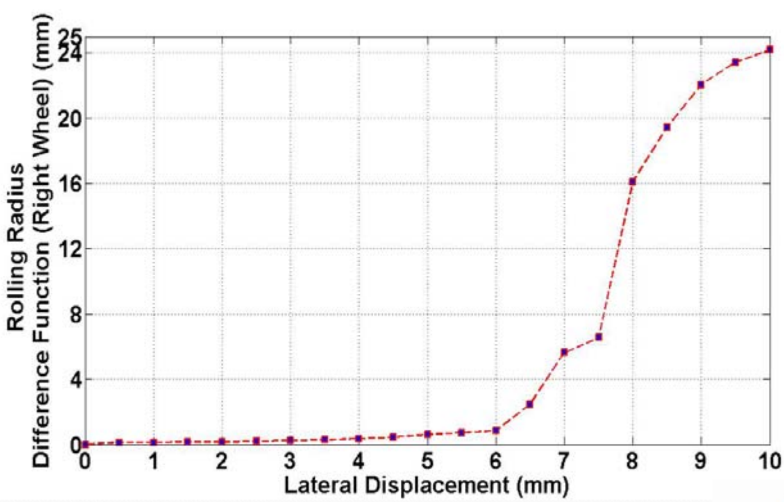
Simulated Results



Rolling radius difference function

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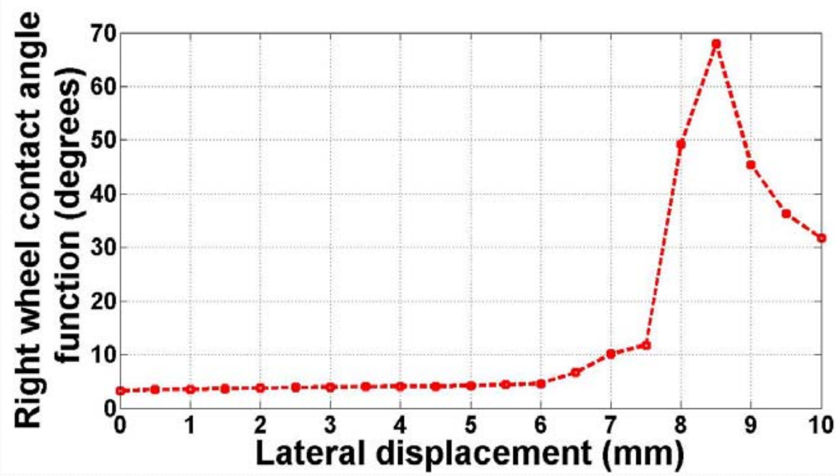
Simulated Results



Contact angle function

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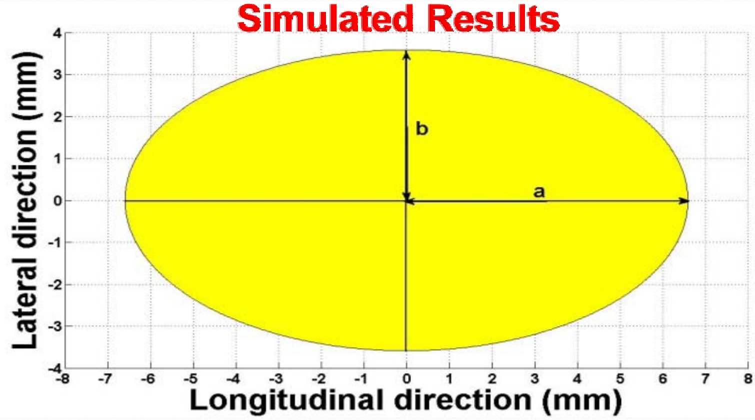
Simulated Results



Contact patch the wheel-rail at central position
a = 6.6673mm, b = 3.5872mm

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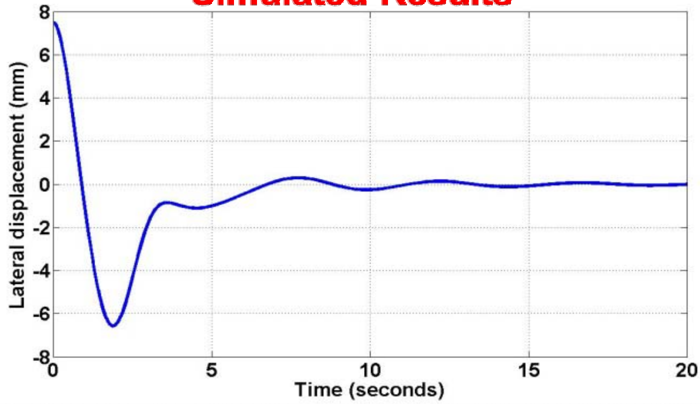
Simulated Results



Lateral displacement of the wheelset
Forward velocity (V = 2.5m/s)

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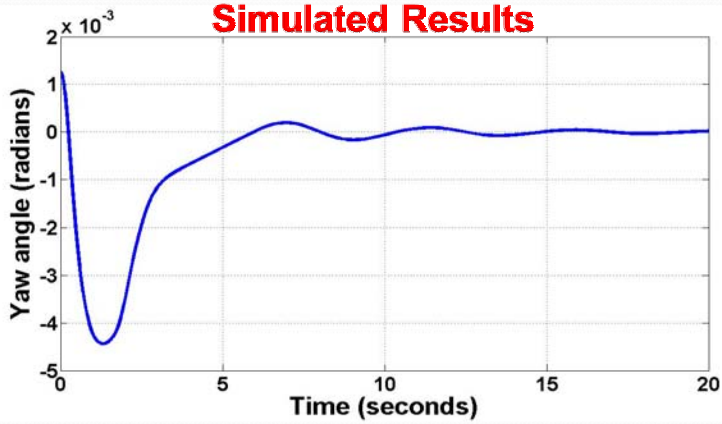
Simulated Results



Yaw angle function of the wheelset
Forward velocity (V = 2.5m/s)

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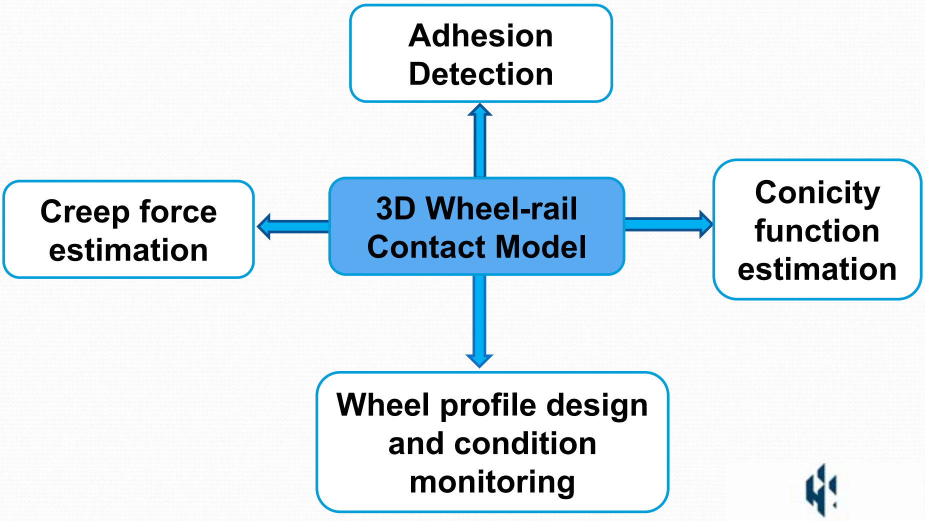
Applications



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ESTIMATION OF RAILWAY VEHICLE DYNAMIC PARAMETERS

USING MOTOR DRIVE BEHAVIOUR

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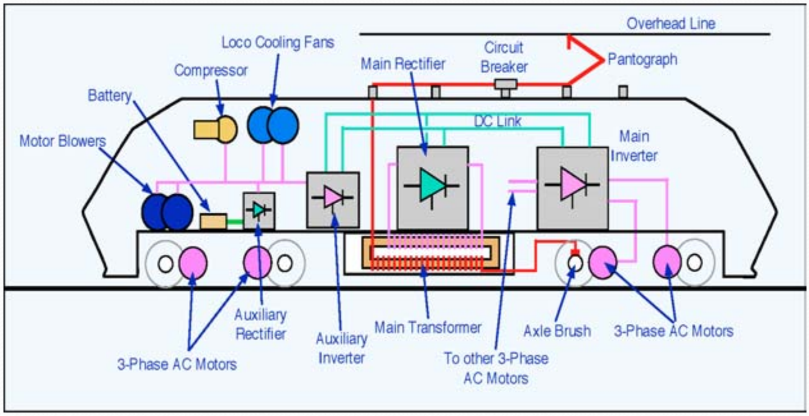

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Future contributions

<u>Technologies for accurate measurement and prediction</u>

- traction and wheel slip/slide control
- estimation of vehicle-track dynamics, wear and adhesion
- system integration for rail wheelset steering and traction control

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Future contributions

Technologies for accurate measurement and prediction

- measurement of train ground speed with intelligent data processing
- independent wheel set dynamics
- parameter identification
- automated and adaptive model-based prognostics using Monte Carlo simulation, particle filter

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Future contributions

Mechatronic trains of the future

- remote condition monitoring with wireless intelligent sensors for effective high speed maintenance and inspection of train and track
- moving-load dynamics

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Future contributions

Mechatronic trains of the future

non-linear autonomous systems

- **process monitoring, modelling, control and optimal design**

- **expert systems**

cognitive systems engineering

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With acknowledged contributions from

Professor Andrew Ball

Mr Arthur Anyakwo